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Practice and Outcomes of Multidisciplinary Research for Environmental Sustainability

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Since about 1990, when sustainability became a key concept for a wide range of scientific disciplines, the need for multidisciplinary collaboration has increased. We present five illustrative cases from the long-standing environmental research work at the University of Groningen. The projects described are about hazardous materials risk, odor annoyance, energy scenario evaluation, climate decision analysis, and household consumption, respectively. The various case discussions emphasize experiences in research conceptualization, project design and execution, main findings, policy advice and surplus value, and difficulties met. Conclusions and recommendations are presented about the practice of multidisciplinary research. Finally, some challenges for research and development about environmental sustainability are discussed.

Real-life issues hardly ever match traditional disciplinary approaches in applied scientific research. However, in the study of environmental problems the natural sciences have long been in the forefront—and rightly so. This is related to the need for assessing the state of the external environment in various respects. A focus on natural science analyses is traditionally linked to an effects-oriented kind of environmental policy. Knowledge of harmful effects makes one first of all want to combat, mitigate, or compensate for the effects. Thus, for quite a while, the human causation or aggragavation of environmental deterioration was underattended, not only in problem analysis but also in policy interventions. This classical picture of environmental problem solving changed around the time of the

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Brundtland report "Our Common Future" (WCED, 1987), introducing the notion of sustainable development.

Since the late 1980s the sustainability concept has been at the center of both the natural environmental sciences (physics, chemistry, and biology) and a wide range of environmental subdisciplines in psychology, sociology, economics, law, and philosophy (Robinson, 2004). This increased the need for multidisciplinary research. This article aims to demonstrate the nature and the importance of multidisciplinary collaboration; it describes a number of illustrative projects; it summarizes some of the surplus value obtained and difficulties met; and it draws lessons for future research and policy support about environmental sustainability.

Multi-, Inter-, and Transdisciplinarity

There is a substantial literature on the terminology and concepts of collaboration among scientific disciplines. Recent papers in the field of environmental spatial sciences are Max-Neef (2005), Pohl (2005), Ramadier (2004), and Tress, Tress, and Fry (2004). Given the multidisciplinary nature of the research projects reported here we first need to clarify the distinction between multidisciplinarity, interdisciplinarity, and transdisciplinarity.

Multidisciplinarity means that a particular (policy) problem or an (other) observable phenomenon is considered from different disciplinary viewpoints. This eventually involves a confrontation of different scientific approaches (concepts, models, methods, findings), in the hope that together the multidisciplinary research team succeeds in producing a coherent picture of the relevant problem, possible explanations for (parts of) it, and potential solutions.

The biggest hope of a multidisciplinary team is that they are able to construct a common, comprehensive definition of the problem, an explanatory view of relevant mechanisms and processes, and a manageable set of problem solutions. To the extent that the team succeeds, however, they would find themselves in an *interdisciplinary* endeavor, in which relevant parts (concepts, models, methods, findings) of different scientific disciplines are merged together and neatly integrated. Thus, for example, a natural science model about the spreading of air pollution might be coupled to a behavioral science model of using motorized transport; or an economic model of consumer utility maximization might be combined to a psychological model of habit formation and social status seeking. This would extend the scientific basis for effective policy making.

In contrast to multi- and interdisciplinarity, *transdisciplinarity* signifies the crossing of boundaries between scientific and nonscientific communities. Transdisciplinarity represents a set of lively interactions between scientists on the one hand, and representatives of industry, government, and/or civil society on the other. For scientific researchers transdisciplinarity means "reaching out to society." For members of government, industry, and civil organizations it means maintaining contact with science and seeking scientific support and advice whenever needed. This may deepen society's understanding of complex (policy) problems and may prevent the selection of too limited and/or biased problem solutions.

Sustainability in an Applied Sciences Context

Sustainability is a multidimensional concept involving economic security, social well-being, and environmental quality (see also Vlek and Steg, this issue). Essential items on both the research and policy agendas concerning sustainability are the resource intensity of human production and consumption patterns, the assessment and management of natural resource stocks and flows, and societal transitions in various human activity domains. Examples are energy supply and demand, agriculture and livestock production, availability and consumption of drinking water, mobility and transportation, and recreation and tourism. Environmental impacts associated with these activity domains are urban air pollution, greenhouse gas emissions, environmental noise, soil desiccation, and nature degradation. These burdens contribute to reductions in environmental quality and may involve threats to human health and well-being.

Collaboration between the natural and social (environmental) sciences is necessary to understand the complex nature of the problems, to experience the ways in which different contributions can be made from different disciplinary backgrounds, and to offer policymakers a more complete understanding and corresponding set of tools (e.g., technical and behavioral, individual, and organizational) for addressing and preventing policy problems in real-life practice.

However, practicing multidisciplinarity is often challenging. Researchers from different backgrounds have to find each other and get acquainted. They must learn to understand and appreciate each other's perspectives. They must derive a common motivation from the idea that the whole may become more than the sum of its parts. And what should tie them together is the focus on a single problem area, for example, energy use, environmental noise, or external safety. This, however, draws them into a fair amount of practical problem-analytic homework before they can make both their own and their collective scientific contributions and reap the extra benefits of collaborating across disciplinary boundaries. The next section presents a series of practical experiences.

Illustrative Examples of Multidisciplinary Collaboration

Over the past 20 years, a tradition has been developed among the departments of environmental science, psychology, economics, and sociology at the University of Groningen to set up collaborative teams and design joint research projects, acquire funding for them, and then bring them to fruition. This has helped to form a valuable set of experiences in research conceptualization, project design, project execution, policy advice, and after-care in different directions.

Below, five examples of multidisciplinary research are discussed. The projects described are about hazardous materials risk, odor annoyance, energy scenario evaluation, climate decision analysis, and household consumption, respectively. In describing each example, questions will be addressed about plan, process, product, and presentation. We also consider what went wrong, and why and in which respects were the projects particularly successful. The main findings from each project are summarized in a separate box.

LPG/SO_2 Risk Analysis, Perception, and Decision Making

At the request of the Dutch Ministry for the Environment, a team of environmental scientists, technologists, and social psychologists conducted a triple project on the safety of transport and storage of LPG (liquefied petroleum gas) and SO_2 (sulphur dioxide, as used for the bleaching of beet sugar). This 4-year project followed in the wake of an earlier study in which the risks from various activities at home, in diverse industries, and in transportation were statistically estimated ("actual risks") as well as personally judged ("perceived risks") by a large sample of the population around the heavily industrialized Rotterdam harbor area, in comparison to a Dutch control group outside that area (see Vlek & Stallen, 1981). Two conclusions from this early work were (1) that a statistical (frequentistic) estimation of "actual risk" requires a simple risk definition and may be hard anyway for lack of reliable statistics, and (2) that "perceived risk" or riskiness is a multidimensional concept exceeding classical (simple) definitions of risk. Both conclusions imply a warning about the limited possibility of making risk comparisons among different activities.

The idea of the much larger follow-up project about LPG/SO_2 was to really combine the efforts of natural and social scientists and to add a decision-theoretic subproject in which natural and social research results would be integrated. Thus, in a technological, a psychological, and a decision-analytical subproject, LPG transport and storage facilities were examined, perceptions of various involved groups (including LPG producers, gas station attendants, and neighboring residents) were studied, and multi-attribute evaluations of more or less suitable storage and fueling locations were collected. After doing this for LPG, the basic approach was repeated in three subprojects focused on SO_2. The entire project was eventually reported in six volumes totaling over 1,200 pages (see the 80-page summary report by Vlek & Stemerding, 1984; English reports are Vlek, Kuyper, & Boer, 1985, and Kuyper & Vlek, 1984). Box 1 presents the main findings.

Box 1. Main Findings from LPG/SO_2 Risk Analysis, Perception, Decision-Making Project

1. It is technically impossible to assess the probability of specific LPG/SO_2 accidents in a valid and reliable manner.
2. Perceived risk evaluation regarding LPG/SO_2 reflects a subject's overall more or less favorable attitude toward technology-driven developments in general.
3. Nontechnical ("perceived") risk evaluation is more strongly affected by the LPG/SO_2 interest of the subject—positive, neutral, or negative—than by the subjects' relevant expertise or decision power, positive interest going along with favorable evaluation, and vice versa.
4. The provision of balanced, concrete, and relevant information about the nature and the safety of LPG/SO_2 does not lead to major changes in subjects' LPG/SO_2 evaluations.
5. In decision making about LPG/SO_2, interest groups assign their own weights to attributes of "suitable storage alternatives," which results in different preference orders about these alternatives.

This project had a difficult start in which not-yet-experienced team members from different backgrounds had to come to understand each other's language and viewpoints, to develop a commonly agreed research approach, and to communicate fruitfully in order to bring the three projects to useful conclusions. During the entire trajectory, several changes in project management caused delays and gave frictions, which badly combined with the difficulty of the project plan, especially the empirical–psychological subprojects comprising many field interviews with representatives from systematically different interest and expert groups. Actually, the technological, psychological, and decision-analytical subteams did their work in peaceful co-existence, while their main direction and interim results were discussed in overall team meetings. Major, effective efforts to integrate the results of the subprojects were undertaken during the writing and composition of the final report.

Contacts with policymakers and other potential users were maintained regularly throughout the project, as the funding ministry had installed a "heavy" supervisory committee consisting of about 15 industrial safety experts from the ministry itself, the provincial government of Groningen, and different branches of industry, including the LPG and the beet sugar industries. After publication of the final report, after-care was provided by way of various conference presentations, conversations at the Ministry for the Environment and with other interested parties, in-class lectures for environmental science students, and discussions in several English publications. Further spin-off emerged in several students' working papers and master's theses. Invitations for, and participation in, various conferences about industrial risks and environmental safety went on for several years after the project's conclusion. One evident lesson was that a research team should schedule such activities, especially publications, in time and allocate needed resources beforehand.

In retrospect, one might say that a multidisciplinary project of this size needs a clear and solid organizational structure and dependable coordination. It needs time for team members to get accustomed to each other's worlds of thinking and measurement. To keep individual team members mutually tuned and commonly motivated, a social life as well as a "business" life is needed; after a while, project members should get along well with one another. Obviously, a project like this needs the unfailing support of its sponsors and supervisors who should, when needed, assist team members in acquiring the cooperation of external parties.

This project had clarified and supported the notion of the environmental safety of specific hazardous materials in a time when sustainable development had not yet become a popular concept. Many practical suggestions for enhancing the safety of LPG/SO_2 came to light, useful insights were obtained in systematic differences in risk perception among various stakeholder groups, and it appeared that the multiattribute evaluation of LPG/SO_2 sites, too, reflected the effects of differences in the interests at stake. Both conceptually and methodologically this project has been a rich source of new insights (e.g., Box 1) that would not have emerged if the participants had worked independently.

Industrial Odor Annoyance

The dose–effect relationship between an environmental stressor (crowding, risk, noise, heat, malodor) and the exposed person's response is notoriously weak. Often the greater part of the variance in subjects' responses can be explained by other factors (see also Miedema, this issue). One research approach here is to apply a transactional stress theory (Lazarus & Folkman, 1984) in which reactions to and coping with stress are seen as following from the balance between environmental (demand) and personal (capacity) characteristics.

The primary aim of the PhD project discussed here was to clarify the relationship between objective exposure to adverse environmental conditions—*in casu* odorant concentrations, and subjective reactions—*in casu* odor annoyance and subjective health complaints as resulting from the exposure. The research team consisted of a physicist, a psychologist, several research assistants, and advisors about methodology, subjective health assessment, and the concept of stress. The project was funded by the Netherlands Organization for Scientific Research NWO.

This project was a fine case of need and necessity of multidisciplinary cooperation between physicists and psychologists resulting in a clear surplus value of the project results. With the help of a physical dispersion model of odorant concentrations (see Harssema, 1987, for a review) the team was able to identify spatial contours (or plumes, depending on wind force) of equivalent odor concentrations around relevant factories producing beet sugar, cigarette tobacco, mushroom manure, and cattle fodder, respectively.

On particular days, after weather (especially wind and humidity) conditions being taken into account, around each factory several contours of greater and lesser odor intensity were determined, whereupon the psychological researchers sent out trained interviewers to people living within the contours, in order to collect raw data about their perceptions, experiences, judgments, and preferences about being (variously) exposed to the odorous atmosphere in their living environment. Apart from personal variables such as education, health status, and internal–external locus of control, certain socioeconomic and demographic characteristics were assessed as well, particularly people's relationship to (or their interest in) the factory under consideration. The main findings are given in Box 2.

Box 2. Main Findings from Cavalini's (1992) Study on Odor Annoyance

1. On average, higher odorant concentrations result in higher levels of reported odor annoyance.
2. Those who are *less* exposed to malodor, more strongly believe it to be bad for their health.
3. Odor exposure itself only leads to health complaints when annoyance is also reported.
4. Economic dependency on (e.g., employment at) a factory leads to significantly lower reported odor annoyance.
5. Reported annoyance about average long-term exposure and specific short-term exposure is very similar.

The project yielded a well-distributed PhD monograph (Cavalini, 1992) and several journal publications (Cavalini, Koeter-Kemmerling, & Pulles, 1991, in English), and it fitted well in a collaborative framework of environmental scientists and psychologists dealing with environmental stressors such as noise and risk. The general messages for policymakers are that environmental stress has an external, physical side as well as an internal, psychological side, which makes natural–social science collaboration indispensable, and suggests that environmental stress policies should be oriented toward both the physical environment and the personal characteristics and circumstances of the people exposed.

Scenario Analysis for Low Energy Consumption and Low CO_2 Emissions

In the Netherlands, between 1989 and 2000, there has been a substantial National Research Program (NRP) on Global Air Pollution and Climate Change. The NRP Global Change was organized along five thematic lines of interest: (1)

The climate system, (2) Causes of climate change, (3) Consequences of climate change, (4) Integrated modeling, and (5) Sustainable solutions for climate policy; see Zwerver, Van Rompaey, Berk, and Kok (1995) for a two-volume report on Phase I (1989–1994) of the NRP. Under Theme (5): "'Sustainable solutions . . . ,'" a project was funded entitled "Analysis of the social significance of long-term low-energy and low-CO_2 scenarios for the Netherlands" (SCAN—SCenario ANalysis, for short). The project was conducted by a seven-person team of sociologists, psychologists, economists, and environmental scientists (see Moll & Biesiot, 1995).

The SCAN project aimed at improving long-term low-energy/low-CO_2 scenarios for the Netherlands, and to clarify them in terms of their significance, acceptability, and feasibility from environmental, social, and economic perspectives. The scenario variants (see Table 1) were tuned toward the domains of greenhouse horticulture, industry, freight transport, and households. In SCAN, the following research questions were addressed:

1. What would be subjects' expected quality of life within several domain-oriented variants of a long-term low-energy/low-CO_2 scenario?
2. What is the social acceptability of the proposed scenario variants?
3. What is the feasibility of the different elements of the scenario variants?

In the first phase of SCAN, a multidisciplinary assessment was made of the process of scenario construction. Here, reference was made to several long-term

Table 1. Policy Scenarios for Greenhouse Horticulture, Industry, Freight Transport and Households, Respectively, in Terms of General and Domain-Specific Energy-Saving Measures

<table>
<tr><th>Greenhouse Horticulture</th><th>Industry</th><th>Freight Transport</th><th>Households</th></tr>
<tr><td colspan="4">- Introduction of a 100% energy tax in the European Union, compensated by lower taxes on labor</td></tr>
<tr><td colspan="3">- Voluntary agreements on energy-saving measures, information, and subsidies</td><td rowspan="2">- Energy standards for new and renovated houses
- Restrictions on car parking
- Road pricing
- Non-motorised infrastructure
- Car-pooling
- Stimulating public transport
- Introducing company transport management</td></tr>
<tr><td colspan="2">- Application of co-generation of heat and energy
- Introduction of Environmental Management Plans for Business Companies
- Improved access to the energy market, e.g., for decentrally generated electricity
- Regulation of energy-savings via environmental permits</td><td>- Various technical measures regarding fuels, engine design, vehicle mass reduction, rolling and drag resistance
- Infrastructure favoring transport by rail and water
- Allowance of larger transport quantities and return-loads</td></tr>
<tr><td>- Setting quota on natural gas consumption</td><td>- Realizing production energy cascades</td><td colspan="2">- Limiting maximum speed via car speed limiters
- Raising fuel excise tax</td></tr>
</table>

socioeconomic scenarios for the Netherlands, as earlier constructed by the Dutch Central Planning Bureau (CPB, 1992). This assessment led to the conclusion that the exclusively economics-based CPB scenarios did not fulfill the multidisciplinary requirements of the SCAN project. Since CO_2 emission reduction had not been a major objective of the CPB scenarios, the predicted reduction of emissions in these scenarios was either absent or insufficient. Moreover, the CPB's macroeconomic evaluation of the societal effects of various CO_2 reduction measures had not addressed the behavioral and institutional effects resulting from these measures.

Therefore, in the second phase, a specific SCAN project scenario was constructed. This contained a number of general policy measures, supplemented by domain-specific sets of measures for greenhouse horticulture, industry, freight transport, and households, together representing about 80% of total energy consumption in the Netherlands. The various policy measures were designed via prior interviews with a number of experts in energy use and environmental effects, and they were detailed with respect to their overall energy and CO_2-saving potentials. Table 1 illustrates the kind of general as well as domain-specific measures making up four particular SCAN policy scenario variants.

In the third phase, each SCAN scenario variant was evaluated in terms of its acceptability, its feasibility, and its consequences for people's expected quality of life. A two-step scenario evaluation was performed in a multidisciplinary way, as follows.

1. A social-psychological subproject was directed at understanding and predicting the acceptability of the (household) scenario measures at the individual level; this yielded an analysis at the micro-level of society, reflecting a relatively short time perspective. Data were collected via a structured 45-item questionnaire filled in and returned by a representative sample of 1,150 household respondents (out of 3,000 originally invited).
2. A sociological subproject was directed at understanding the institutional problems concerning scenario implementation, and at predicting the (political) feasibility of the relevant policy measures for the four sectors. This yielded an analysis at the meso-level, reflecting an intermediate time perspective. Data collection took place via 24 personal interviews with domain-specific experts and key informants as regards energy policy.
3. An environmental–economic subproject was directed at the analysis of the long-term significance of the scenario for the economy of the Netherlands; this yielded an analysis at the macro-level of society, reflecting a relatively long time perspective. Separate attention was paid to distributional, structural, and institutional issues in estimating scenario impacts on economic processes in the four domains under consideration.

Box 3. Main Findings From SCAN Subprojects on Long-Term Low-Energy/Low-CO_2 Scenarios

1. Based on interviews with various experts, reasonably complete and consistent energy-and-emissions scenarios could be developed, involving substantial reductions in fossil fuel use and CO_2 emissions.
2. Household respondents generally preferred the 10 separate policy measures (cf. Table 1, last column) over the scenario package as a whole.
3. There were large differences in the overall expected quality-of-life impact of the scenario, where income ("less important"), environment, and health ("most important") stood out as perceptually most likely to be affected.
4. The meso-level acceptability of the policy measures directed at households was higher if the positive outcomes ("health" and "environment") were stressed while the negative outcomes on people's quality of life (e.g., "income") were underrated.
5. For the production sectors, the (environmental–economic) judgments concerning acceptability and feasibility of the policy measures implied that total energy use in these sectors would still continue to grow. A general energy tax would be acceptable only when introduced step by step.

After completion of the three subprojects the overall project results of the first three phases were integrated in the final phase of the study. English SCAN reports are Kamminga, Slotegraaf, Van der Veen, and Moll (1995), Moll and Biesiot (1995), and Slotegraaf and Vlek (1996). One of the team members wrote a doctoral thesis partially based on his work in SCAN (Kamminga, 2001). Box 3 presents the main project findings.

The SCAN research has led to various policy recommendations concerning the design of low-energy and low-CO_2 scenarios along multidisciplinary lines, further development and application of the relevant methodology, and the promotion of the social acceptance of policies aimed at energy saving and CO_2 emission reduction. The multidisciplinary collaboration within the project was essential and functioned well largely due to experience gained in preceding projects in which key team members had successfully worked together.

Decision Analysis for Integrated Assessment of Climate Policies

The decision analysis project to be described was also funded by the NRP Global Change introduced previously. One of the Theme–4 (Integrated modeling) projects was entitled: "Using decision analysis for the integrated assessment of the climate change problem." The project was carried out by a social science methodologist, a decision psychologist and a physical environmental scientist; see Van Lenthe, Hendrickx, Biesiot, and Vlek (1997).

Van Lenthe et al. started on the premise that the climate problem confronts policymakers with multi-attribute decision making under conditions of uncertainty. If considered serious enough, the problem should evoke alternative policy strategies (including “doing nothing”), all of which involve significant risks for society, its economy, and the natural environment. By conceiving of climate change as a strategic decision problem, policymakers may more easily come to grips with the question: “what should be done about it?” The project aimed at demonstrating the usefulness of decision-analytic thinking and methodology in structuring climate change as a policy problem.

Decision analysis (Raiffa, 1968) begins with problem structuring, whereby a complex policy problem is explicated into policy options, uncertain events, and possible consequences. In a well-defined, fully delineated decision problem, one may then calculate for each policy alternative the average expected utility of its possible consequences, given that one has first assigned probabilities to outcomes of uncertain events and utility values to the various possible consequences. The option with the highest expected utility is taken as the best choice. The latter, of course, is a direct function of the input elements, and it may well change as a result of one or more sensitivity analyses serving to test the robustness of the “best choice” by varying one or more inputs to the entire problem analysis.

For complex policy problems such as climate change, several structuring and analysis techniques exist. For the present project the influence diagram methodology (Oliver & Smith, 1990) was chosen to develop a compact and insightful representation of the climate change problem. A hierarchical ordering of various influence diagrams makes it possible to consider the climate change problematic at different levels of generality and precision. At one level this approach may offer a general overview of the problem as a whole. At another level one may zoom in on specific problem components to conduct, for example, a partial quantitative analysis. Van Lenthe et al. (1997) worked with a “basic causal chain” for the overall problem indicating that *abatement* policies are aimed at human causes while *adaptation* policies should help the “human system” to live with the consequences. The influence diagram approach to the problem of climate change was numerically illustrated for a general-level example in which the risks of several different policy strategies were identified and evaluated.

In addition, the approach was utilized for the specification of important topics for further NRP Global Change research (Van Lenthe, Hendrickx, & Biesiot, 1995). One immediate conclusion was that climate change research thus far was predominantly directed at understanding more of the atmospheric processes (the “climate system” and ecological impacts), while far less research was devoted to an analysis of socioeconomic risks and opportunities in relation to climate change.

With respect to climate policies it was concluded that abatement policies (aimed at human causes) were given more attention than adaptation policies, which in Phase I of the NRP were hardly investigated at all. Moreover, the effectiveness of various strategies to realize relevant policy goals was underattended in the NRP-I. Box 4 lists some of the main findings.

Box 4. Main Findings from the Climate Decision Analysis Project

1. Decision analysis in general and influence diagrams in particular constitute an appropriate policy-oriented approach for the integrated assessment of the global warming problem.
2. This methodology enables a transparent and understandable problem representation in which a basic causal chain underlying climate change is linked to human activities and possible responses.
3. The approach facilitates policy development by identifying the possible decisions and actions in responding to global warming, along with their various kinds of consequences.
4. Through uncertainty and sensitivity analyses the approach supports the recognition of critical knowledge gaps.
5. The approach and the first integrated models are useful points of departure for further research, which should involve an iterative process of modifying and adjusting the modeling approach.
6. In future work, attention should shift from the methodology to the content of integrated assessment.

Altogether, this project has demonstrated the feasibility and potential of a decision-analytic approach in using influence diagrams to come to grips with climate change as a policy decision problem (see also Dowlatabadi & Morgan, 1993).

Toward Sustainable Household Consumption

Modern, "western industrialized" households consume lots of goods and services often produced in far-away places and brought to them via complicated transportation systems (see Stern, Dietz, Ruttan, Socolow, & Sweeney, 1997, for another multidisciplinary inventory). To reduce environmental impacts, it is important to clarify the behavioral motives and mechanisms that are operating here, as well as the physical and technical improvements in the underlying systems and processes that would be possible. Households vary according to many different characteristics, such as income, composition, size, values, and lifestyle. Household expenditures are associated with the direct and indirect use of energy. Direct energy comprises the fraction of energy consumption that is literally consumed by a household, for example, natural gas, electricity, and motor fuels. Indirect energy use is involved in the production, delivery, and waste disposal of consumer goods and services.

The large-scale multidisciplinary research program HOMES (HOusehold Metabolism Effectively Sustainable, 1994–2000) was designed to investigate household consumption, based on available as well as newly gathered data from the Netherlands, in relation to relevant environmental impacts. The HOMES program was funded by NWO, the Netherlands Organization for Scientific Research, through its priority program on Sustainability and Environmental Quality. The term "household metabolism" refers both to the demand for resources, that is, the direct flow of resources through households, and to the supply of resources, that is, the materials and energy indirectly required to realize these flows (e.g., in mining, production of materials, construction of houses, and goods manufacturing); see Van der Wal and Noorman (1998). HOMES was aimed at developing and applying concepts, methods, and models relevant to the diagnosis and evaluation of household metabolism in a complex western society. Since this type of metabolism was not expected to be sustainable, HOMES also focused on the changes that would be necessary to accomplish a transition to a kind of household metabolism that could be called sustainable.

The retrospective diagnosis and future evaluation phase of HOMES covered the period 1950–2050 (see Noorman & Schoot Uiterkamp, 1998). Household functions included in the study were infrastructure, heating, mobility, white goods appliances, and the consumption of water, natural gas, and electricity. The overall environmental impact resulting from household metabolism was determined by the number and size of households, by the consumption per household, and by the material and energy efficiency of consumption. The latter is a function of biophysical, technical, economic, spatial, and behavioral factors as well as specific social institutions and administrative policy measures.

Therefore the HOMES program brought together about 12 researchers from the environmental sciences, economics, policy science, psychology, and spatial planning science. The approximately 30 person-year program involved PhD students, post-docs, and senior staff assisted by several master's degree students. The policy scientists were from the University of Twente, and the others from the University of Groningen.

The combined results of all subprojects overwhelmingly showed that the environmental burden of household consumption had enormously increased since about 1950, and that the present-day environmental burden of household consumption patterns may be significantly transformed. This would result in sustainable activity patterns involving much less fossil fuel use and much lower greenhouse gas emissions (see Noorman & Schoot Uiterkamp, 1998), along with only moderate changes in people's quality of life.

The surplus value of a multidisciplinary approach was clearly demonstrated throughout the HOMES project. Consider two examples. First, natural science analyses of past and projected future environmental impacts of household consumption patterns are useful. But by combining research outcomes, social science assessments of cost-effectiveness, feasability, and acceptability made them more realistic and valuable. Second, within HOMES several useful multidisciplinary instruments were developed. One of them is an "impact-oriented measure for environmental behavior" (Gatersleben, Steg, & Vlek, 2002). Psychologists often focus on environmentally less relevant behaviors, while natural scientists tend to ignore behavioral processes. The HOMES approach involves calculating overall energy use of households based on their possessions and behaviors, and it proceeds by evaluating their socio-demographic and motivational determinants. The main project findings are shown in Box 5.

Box 5. Main Findings from the HOMES Program on Household Metabolism

1. Driving forces for household metabolism are demographic factors (e.g., population growth, decrease in household size), economic factors (e.g., rising spending capacity, decreasing prices of goods and services), increasing opportunities and abilities (e.g., availability of services, leisure time), and public policies (e.g., "equal opportunity," welfare provisions).
2. Counteracting forces for household metabolism are technological innovations resulting in efficiency improvements, specific policy measures (e.g., environmental taxes) and public concerns about consumption and environmental problems.
3. There is a strong relation between spatial land use and energy use of households.
4. Consumption itself strongly depends on structural factors (see above), while *changes* in consumption depend on cognitive and motivational factors.
5. Direct feedback to households (e.g., through customized websites) may make people more aware of the environmental consequences of their behavior.
6. Liberalization and internalization of energy markets may require financial incentives such as higher offsetting taxes to reduce energy use of households.

The specific household perspective chosen in the HOMES program proved to be useful and relevant. However, research at the household level may overlook solutions and transition routes at lower- and higher-scale levels, respectively. Follow-up research was therefore aimed at specific needs and requirements of individual households as well as on higher aggregates of households such as cities and city quarters both in the Netherlands and abroad. To address the latter issues the HOMES program was followed and elaborated upon by the EU project "Toolsust," aimed at stakeholder involvement in developing and implementing practical tools for the promotion of sustainable households in European countries and cities (Kok, Falkena, Benders, Moll, & Noorman, 2003).

The HOMES program was highly productive and successful. It resulted in a monograph (Noorman & Schoot Uiterkamp, 1998), six PhD theses, some 20 papers in peer-reviewed scientific journals (e.g., Biesiot & Noorman, 1999; Gatersleben et al., 2002; Ligteringen & Kamminga, 1998; Linderhof, Kooreman, Allers, & Wiersma, 2001; Noorman, Biesiot, & Moll, 1999; Van Diepen & Voogd, 2001;), a workshop in 1995 at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg (Austria), an international conference in Groningen (1999), and a range of other conference presentations and reports.

When the program was started in 1994, environmental studies aimed at households were rare. Ten years later they were rather common; see, for example, the special issues of the *Journal of Industrial Ecology* (2005, *9*, 1–2) and *Sustainability: Science, Practice and Policy* (2005, 1, 1). The household level is now included in policy documents of governments and international organizations like the European Environment Agency and the Organization of Economic Cooperation and Development, and it has been elaborated for the Industrial Transformation subprogram of the International Human Dimensions Program on Global Environmental Change IHDP; see Vlek, Reisch, and Scherhorn (2000). Studies from the household perspective turn out to complement consumer studies and urban studies.

In HOMES, the main everyday burden of research fell on the shoulders of PhD students. Their strongly interlinked research plans had been prepared by senior staff members as part of the grant application procedure. Therefore, the PhD students had to get familiar not only with their own disciplinary research plans but also with those of colleagues working in other disciplines. In the beginning they cooperated closely under the guidance of the post-doc coordinator who maintained close ties with the program chairman and the other senior staff members. Later on the PhD students parted ways because they all had to finish their own PhD thesis. The various individual research trajectories sometimes interfered with the need to arrive at a common synthesis. This potential conflict was solved by conducting regular research seminars, by writing joint papers, by organizing workshops and a concluding international symposium, and above all by writing a common monograph. Substantial contributions of the project coordinator and the senior staff were critical factors in the final phases of the program.

Cases, Lessons, Benefits, and Recommendations

Multidisciplinary research tends to be either discipline-driven or problem-driven. Examples of discipline-driven, "bottom up"-initiated research are the "LPG/SO_2 risk" and "Odor annoyance" projects discussed above. In these two cases, researchers with a social science background had instigated natural scientists to collaborate. Alternatively, in problem-driven projects, research money often comes from specific "top down"-initiated research programs of national or international (e.g., EU) funding agencies. Examples from the cases presented are the "Scenario analysis," "Climate decision analysis," and "Household metabolism" projects discussed above. Regardless of the bottom-up or top-down character of the project, the need to address real-life environmental issues gave rise to the multidisciplinary research designs eventually adopted.

In the LPG/SO_2 risk project the traditional technology-based quantitative risk concept was found to be lacking a perceptual counterpart, while both sides were weak in decision-theoretic significance. The input from psychology and decision theory resulted in a much more realistic risk concept that also turned out to be a solid basis for initiating and implementing decision-making guidelines. The Odor annoyance project dealt with the well-known difficulty of measuring and quantifying malodor. Physico-chemical odorant dispersion models produce only source-related odor concentration patterns. Since odor observation underlies the subject's possible annoyance, the human nose is still indispensable to calibrate and validate the odorant dispersion models. In the SCAN project, energy conservation scenarios were subjected to a three-pronged approach aimed at the issues of economic cost-effectiveness, feasibility, and social acceptability. This resulted in an improvement of the quality and realism of such scenarios. In the Decision Analysis project, combining the relevant disciplinary approaches turned out to be indispensable. The results of natural science-based climate modeling and scenario building were subjected to social science-based evaluation and assessment procedures. This may lead to more realistic policy decision making since uncertainties in climate modeling are coupled to human risk perceptions. In the HOMES program, efforts from the various disciplinary approaches resulted in useful outcomes for fields like consumer policy making, environmental communication, and urban planning.

Formulating Policy Implications

Across the various collaborative projects conducted we have experienced that offering policy suggestions from multidisciplinary research often poses challenges. One reason for this is that the researchers and the policymakers may perceive the original or a current (seemingly fitting) policy problem rather differently. Thus good and early communication between researchers and policymakers is important. Second, policy problems generally have a dynamic character. While researchers may need a stable problem formulation for the duration of their (say, 3-year) project, policymakers may be confronted with changing circumstances whereby their original problem may be significantly transformed. Third, research may address only part of the policy problem because it would be infeasible to cover an entire policy-making process.

Some Recommendations

For those who plan to undertake multidisciplinary research, we offer the following practical recommendations.

1. Multidisciplinary research collaboration may best be started in the problem formulation and planning stages of a project. Questions about the what, why, how, with whom, and for whom need careful discussion, as well as the usefulness of expected results.
2. Before establishing the definitive research team it is useful to discuss the research plan and get potential participants to agree on the basic approaches delineated and the tasks set. Possible feelings of unease may be resolved through revisions of the initial plans.
3. When establishing the team, make sure to explicate and agree on overall program management and everyday work coordination.
4. Right from the beginning, the position of individual researchers should be well secured versus their home group and their home discipline, for example, as regards teaching obligations, journal publications and other efforts aimed at "advancing the discipline."
5. To prevent delays due to collaborators waiting for one another, it is wise to make distinct subprojects relatively independent from one another.
6. Multidisciplinary research involves research done by differently trained and experienced people. The research process ideally involves regular confrontations, collaborative meetings, coordinated data collection, joint publications and, eventually, active collaboration with regard to practical policy development and support.
7. Starting a multidisciplinary project is easier than concluding it. Given the nature of multidisciplinary research, both initial divergence and later convergence are comparatively hard to control, but the latter more so than the former. For project coordinators, "coming down and landing safely" is a special challenge, which should be faced and taken up well before one starts writing the final report.
8. External funding and accountability may limit opportunities for practical policy support and for scientific publications. It is prudent, therefore, to reserve enough time and resources to (also) accomplish these "harvesting" jobs.
9. Scientific publications from multidisciplinary projects still are rather hard to do via well-established, high-level scientific journals. To stimulate and reward multidisciplinary research, the receptivity of editorial boards would need to increase.

In all cases presented before, we have seen substantial benefits and surplus values emerging from the multidisciplinary research designs. Yet the benefits may carry a price. Multidisciplinary collaboration is neither good for any project nor for everybody. Transaction costs may be high both in terms of resources and time. Adequate project planning is a must and should preferably include steps toward communicating and implementing results. Energy scenario construction, industrial design, transportation, land use planning, and environmental risk management are but a few examples of areas where multidisciplinary research and policy support may be highly useful.

General Conclusions and Suggestions

The call for multidisciplinary research on environmental problems first arose during the 1970s, particularly in connection with nuclear reactor safety (e.g., WASH-1400, “the Rasmussen Report,” 1975). Technical risk analysis started to develop, but its counterpart, the study of laypeople’s risk perceptions, followed in its wake; see Lowrance (1976), Fischhoff, Slovic, Lichtenstein, Read, & Combs (1978), and Vlek and Stallen (1981), among others. After a while, other environmental topics elicited multidisciplinary involvement as well: traffic and transportation, energy consumption and savings, nature preservation, and, of course, global warming and climate change. Nowadays, there are several multidisciplinary publication channels such as, the *Journal of Industrial Ecology, Global Environmental Change*, and the *International Journal of Sustainable Development.*

For quite a while, however, in many policy-oriented exercises, various disciplinary approaches got their turn under the label of “aspects”; one might do research—or teach—about the environmental, economic, psychological, or geographic “aspects” of a given kind of policy problem without being invited, or forced, to integrate much from the different scholarly disciplines involved. The real challenge, of course, is to go beyond the explication of relevant “aspects” of a certain problem and to analyze and investigate it, theoretically as well as methodologically, from different disciplinary perspectives. Both the various approaches adopted and the different results obtained should then be confronted among each other. Researchers from a particular discipline may thus come to understand the limitations and shortcomings of their own approach in conjunction with the reasons why the others’ perspectives, methods, and findings are indispensable. An important requirement for effective collaboration is that all parties involved, social as well as natural scientists, work with unambiguous concepts, clear theoretical models, and valid measurement methods, so that their project contributions are solid and understandable.

Actually, embarking upon a multidisciplinary research project may be initially alienating, and it may turn out to be painful as well as rewarding (cf. Tress, Tress, & Fry, 2005). It may alienate one from one’s home base in a given disciplinary group or department. It may be painful for the exposition of your own relative ignorance in view of others’ know-how. But after all it may be rewarding for the broadening of your intellectual horizons and the effectiveness of a collaborative policy advice. Yet, one may always be faced with the question: "How far should one go?": in making yourself familiar with the practical policy domain under consideration, in lending your ears to colleagues trying to "sell" a completely different view of the problem at hand, or in transgressing the boundaries of "pure science" in attempting to support policymakers in handling their own immediate policy problem more effectively.

In the authors' view, multidisciplinary research often takes place in a science–society arena that is ideally suited to test and uphold the rules of the game called science: concisely describe and explain this or that problematic phenomenon; find out and predict how things work; be aware of the directive power of conceptual frameworks; consider alternative hypotheses; try and evaluate different methods; approach and exploit various data sources; check for validity and consistency; be detached from political power play; be explicit about the values your clients cherish; and be sensitive to the often subtle play of your own values in determining the design and direction of your research. In this respect it may be worthwhile to engage the real stakeholders (who may use the results) in an early stage of your research planning.

Challenges for Sustainability Research and Development

Sustainability is a socially founded, policy- and action-oriented multidimensional concept. As a topic of scientific concern it may attract scholars from various disciplines. These may eventually be assembled into a research area called "sustainability science" (Clark & Dickson, 2003; Swart, Raskin, & Robinson, 2004). In October 2000, the participants of the "Friibergh Workshop on Sustainability Science" formulated the following statement that nicely captures both the concerns and the aspirations underlying the present article:

> The world's present development path is not sustainable. Efforts to meet the needs of a growing population in a globalizing, unequal and human-dominated world will continue to exert unsustainable pressures on the Earth's essential life-support systems. . . . Meeting fundamental human needs while preserving the life-support systems of the Earth will require a worldwide acceleration of today's halting progress in a transition toward sustainability. . . . What is urgently needed now is a better general understanding of the complex dynamic interactions between society and nature so that the alarming trend towards increasing vulnerability is reversed. (Friibergh, Sweden, 11–14 Oct. 2000; see http://www.earthethics.com/friiberg_workshop.htm).

Scientific disciplines have a general theory-oriented purpose and they focus on the enhancement and improvement of descriptive, evaluative, and/or prescriptive knowledge (Gasper, 2001; see also Max-Neef, 2005). However, isolated monodisciplinary approaches or a noninteracting set of separate disciplines are insufficient for an adequate understanding of rather complex societal problems, of which (un)sustainable development is an urgent example. Instead, multidisciplinary or even interdisciplinary approaches are called for.

But to quote Brewer: “the world has problems but universities have departments” (Brewer, 1999, p. 328). University departments tend to stick to their organization along different mono-disciplines because—obviously—students first have to thoroughly learn a well-delineated trade, perhaps up to the level of a doctoral dissertation. Universities at large tend to protect existing “central” disciplines, if only to shield the generation and transfer of knowledge from outside (e.g., political) interference. However, the protection of the specific characteristics of disciplines interferes with the need for interdisciplinary collaboration about vital issues such as social, economic, and environmental threats, which transcend their regular boundaries.

For these reasons academic researchers collaborating successfully in multidisciplinary projects have to live up to specific requirements (Weingart & Stehr, 2000). They must be (creatively) experienced in their own branch of science, they must be interested in practical, (nonlaboratory) problems, they must be strongly motivated to develop a common, multidisciplinary understanding, and they must be tolerant and socially capable of dealing with initial misunderstandings, the need to repeatedly explain their own view, and to listen carefully to what experts from other backgrounds have to offer. This, taken together, may well require the formation of special (long-term) teams of experts from different disciplines, whose task it is to provide a thorough understanding and a useful set of management ideas for specific classes of important societal problems. We conclude that collaboration among colleagues from different disciplines and walks of life generally offers specific rewards for the project outcomes and the participants involved. It may also inspire university students by showing that there is a larger, more complex world waiting for them after they have finished a (largely) monodisciplinary education.

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